# *fib* Report on Design of Concrete Members Strengthened with Externally Applied Reinforcement

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**Abstract.** The last decades, the introduction of fibre reinforced polymer (FRP) reinforcement has been proven instrumental for the strengthening and seismic retrofitting of a large number of ageing concrete structures. FRP reinforcement in the form of strips, sheets, fabrics and bars are used as externally applied reinforcement, by means of dedicated application techniques such as surface bonded reinforcement (often designated as externally bonded reinforcement), near surface mounted reinforcement (applied in grooves in the concrete substrate), textile reinforced mortar (jacketing with reinforced mortar layer), etc.

Work by the International Federation of Structural Concrete (*fib*) resulted in a design guidance document (*fib* Bulletin 14) issued in 2001 for externally bonded reinforcement, and continued by the introduction of FRP reinforcement in Eurocode 8 (CEN 2005) and in the *fib* Model Code 2010 (*fib* 2013). Currently, also a CEN work group is active to introduce FRP reinforcement and strengthening of concrete structures with FRP in the next version of Eurocode 2 (CEN 2004). More recently, *fib* Task Group 5.1 issued an updated version of the *fib* design guideline (*fib* 2017), in succession of Bulletin 14 (*fib* 2001). In this new bulletin the scope is broadened to the before mentioned types of externally applied reinforcement. It covers the various FRP material and strengthening systems which have become apparent, the basic design approaches, the bond interaction, structural behaviour, practical execution, etc. Mainly those aspects are taken into account which form the majority of the design problems for persistent load situations. Moreover, seismic retrofitting is comprehended in a detailed manner.

The new bulletin reflects the evolution in the design of concrete members strengthened with FRP, whereby this concrete strengthening technology has evolved from an emerging one, with first practical applications dating from the 1990's, to a widely accepted technology, with nowadays thousands of applications worldwide.

**Keywords:** Fibre reinforced polymer (FRP) · Externally applied reinforcement (EAR) · Strengthening · Rehabilitation · Design


D.A. Hordijk and M. Luković (eds.), *High Tech Concrete: Where Technology and Engineering Meet*, DOI 10.1007/978-3-319-59471-2_183

## 1 Introduction

Each year, considerable investments in construction engineering are related to maintenance, repair and strengthening (including seismic retrofitting) of structures, following the social and economic needs for a reliable and functional built environment. Key statistics in Europe (EU29, activity year 2015; FIEC 2016) indicate that at least 28% of the total construction output is in repair and maintenance. This is estimated to be even higher for buildings only, at about 50%. The need for repair and strengthening follows several reasons, among which changes in the functional use of structures, damage due to mechanical actions or environmental effects, more stringent design requirements, poor detailing, design and construction errors. Moreover, maximizing the use of the large existing building stock and infrastructure by efficiently and effectively extending their service life is an effective measure to reduce environmental impact.

Several techniques for repair and strengthening are available, many of which relate to externally applied reinforcement (EAR). Especially, the introduction of fibre reinforced polymer (FRP) reinforcement has been proven instrumental for the strengthening and seismic retrofitting of a large number of ageing concrete structures during the last decades. The technology started in the 1960's with steel plate bonding (e.g. Swamy and Gaul 1996) and further developed with externally bonded FRP reinforcement in the 1990's (e.g. Meier et al. 1993). In the new millennium, the use of advanced materials (FRP, as well as novel steel based materials) for strengthening and rehabilitation of deficient concrete and masonry structures is quickly pervading the construction industry and the available commercial systems have been proven economically competitive compared to traditional repair solutions. Though FRP materials are readily used in a growing number of strengthening applications, the industry demand for comprehensive design provisions in line with the latest developments and code formats has been increasingly apparent.

*fib* Bulletin 14 "Externally Bonded FRP Reinforcement for RC Structures" (*fib* 2001) issued in 2001 by *fib* Task Group 9.3 "FRP Reinforcement for concrete structures", has been a milestone document in that sense that it is an often referred and used design guidance document and at that time one of the *fib* bulletin best sellers. Amongst other, it resulted in the introduction of FRP reinforcement for strengthening applications in *fib* Model Code 2010 (*fib* 2013; Triantafillou and Matthys 2013) and for seismic retrofitting in Eurocode 8 (CEN 2005). Currently, also a CEN work group is active to introduce FRP reinforcement and strengthening of concrete structures with FRP in the next version of Eurocode 2 (CEN 2004).

Task Group 9.3 (TG9.3) being renumbered into Task Group 5.1 (T5.1), which resorts under Commission 5 "Reinforcements", now issued an updated version of the *fib* design guideline for strengthening applications by means of FRP (*fib* 2017), in succession of Bulletin 14 (*fib* 2001). This new bulletin, titled "Design of Concrete Members Strengthened with Externally Applied Reinforcement", not only reflects the recent evolutions and information regarding design of concrete members strengthened with FRP, but also broadened the scope to a class of strengthening systems for which the terminology Externally Applied Reinforcement (EAR) has been introduced. The new bulletin gives detailed design guidelines on the use of EAR, the practical execution and the quality control, based on the vast amount of knowledge and innovations built over the years in this field and the expertise and state-of-the-art knowledge of the task group members. The content of the bulletin is discussed in the following section.

# 2 Scope and Overview of the Bulletin

## 2.1 General

This chapter gives an introduction to strengthening and seismic retrofitting of the built environment and introduces advanced composites based strengthening techniques and their benefits. The aim and concept of the bulletin is also presented. At the basis of the document, basic application forms of EAR are denominated as shown in Fig. 1.

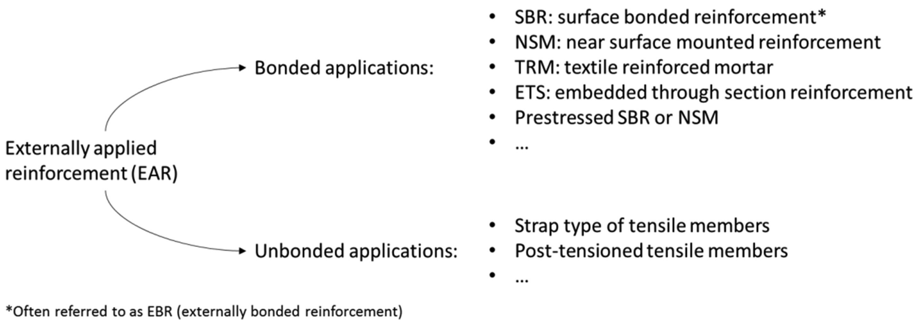


**Fig. 1.** EAR basic application forms

## 2.2 Materials, Systems and Techniques

The selection of materials for different strengthening systems is a critical process. Every system is unique in the sense that fibres and binder components are designed to work together. This implies that a binder for one strengthening system will not automatically work properly for another. Furthermore, a binder for the fibres will not necessarily provide a good bond to concrete. Therefore, only systems that have been tested and applied in full scale on reinforced concrete structures should be used.

The chapter discusses the constituent materials for FRP strengthening, the EAR systems and the techniques for EAR strengthening. With respect to the latter, reference is made to the so-called "basic technique" and to "subsequent or special techniques". The basic strengthening technique, which is most widely applied, involves the manual application of either cured in-situ (so-called hand lay-up) or pre-cured systems by means of cold cured adhesive bonding. This is the so-called classical FRP strengthening technique, denoted as externally bonded reinforcement (EBR) or more precisely as surface bonded reinforcement (SBR). Besides the basic technique, several subsequent or special techniques have been developed, originating from the basic surface bonded FRP systems, e.g. near-surface mounted bars, textile reinforced mortar, prestressing, mechanically anchored or fastened FRP, the use of spacers, embedded through section reinforcement, etc.

## 2.3 Basis of Design and Structural Analysis

This chapter sets the overall framework of requirements applicable to the design of EAR strengthening, being applicable to the design of existing buildings and civil engineering works in reinforced and prestressed concrete, repaired or strengthened by means of EAR systems and as such subject to structural strengthening as defined in EN1504-9 (CEN 2009). The chapter follows an Eurocode-compatible format discussing amongst other reliability management, limit state design, and basic variables both in terms of actions and environmental influences as well as material and product properties. As such, the chapter discusses the basis of design according to the ultimate (ULS) and serviceability limit states (SLS). It is stated that often the latter is governing. Indeed, as FRP materials have high strength, small cross-sectional areas of FRP are needed for satisfying the ULS requirements. In order to meet the serviceability criteria, this cross-section may be insufficient, especially given the relative low modulus of elasticity of some FRPs.

In application of the partial factor design verification method a linear elastic stress-strain relationship for FRP is assumed. In the SLS, reference is made to the mean value of the secant modulus of elasticity, whereby provisions for the calculation of the SLS are given in Sect. 2.7. In the ULS, the provisions of Sect. 2.6 (or Sect. 2.8 in the case of seismic retrofitting) apply, whereby the design stress-strain curve is idealised by a linear response up to the characteristic values of tensile strength $f_{fk}$ and failure strain $\varepsilon_{fuk}$. The slope of this design stress-strain curve refers to a modulus, defined as the ratio of $f_{fk}/\varepsilon_{fuk}$. The design value of the tensile strength is defined as:

$$f_{fd} = \eta \frac{f_{fk}}{\gamma_f}$$

where $\gamma f$ is the FRP material safety factor (Table 1) and $\eta = \varepsilon_{fue}/\varepsilon_{fum}$ normally equals 1, as the effective ultimate FRP strain $\varepsilon_{fue}$ expected in-situ will not significantly differ from the mean strain $\varepsilon_{fum}$ obtained through uniaxial tensile testing, and as small variations are accounted for in $\gamma_f$. However, in certain circumstances, $\varepsilon_{fue}$ may be significantly lower than $\varepsilon_{fum}$, as would occur when wrapping FRP plies around sharp corners, application of a high number of layers in jacketing, multi-axial state of stress, etc. A limiting value of the FRP failure strain may also be considered as a simplified design alternative. In this case, the ULS verification restricts excessive FRP deformations, rather than verifying the related failure mode itself.

Section 2.3, as well as Sect. 2.8 for seismic retrofitting, also give considerable attention to strategies for design and includes design flow charts. It defines provisions for the required deformation capacity at the ULS of members strengthened in flexure (see also Fig. 2), in relation to the safety factor between the service load and the resisting design load. It further defines provisions for the accidental loss of FRP in relation to the degree of strengthening. Indeed, the strength increase of properly

**Table 1.** Material safety factors for FRP tensile strength

| Design situation | Safety factor[a] |
|---|---|
| Persistent/transient | 1.25 |
| Accidental | 1.00 |

[a]These safety factors imply that the quality control provisions on the FRP materials and products, as well as their installation, are according with the provisions of Sect. 2.10. The safety factors adopted in seismic retrofitting are higher, see Sect. 2.8

designed strengthened members will be limited by serviceability and ultimate limit state requirements, as well as deformability provisions. Nevertheless, it is sometimes suggested that the FRP strengthening should serve as secondary reinforcement, so that in case of accidental loss of the FRP strengthening, the existing structure does not (totally) collapse. If the accidental design situation is fulfilled, structural safety is maximized with respect to loss of the externally bonded reinforcement. In this case, special design considerations such as vandalism, impact or fire are generally less of concern. On the other hand, it can be argued that the "secondary reinforcement" rule restricts the maximum strength increase, while sufficient evidence is available to rely on FRP strengthening systems not only as secondary reinforcement, but also as prime force bearing elements. In this case, extra attention should be paid to all relevant accidental situations and the chapter lists specific points for the designer toider.

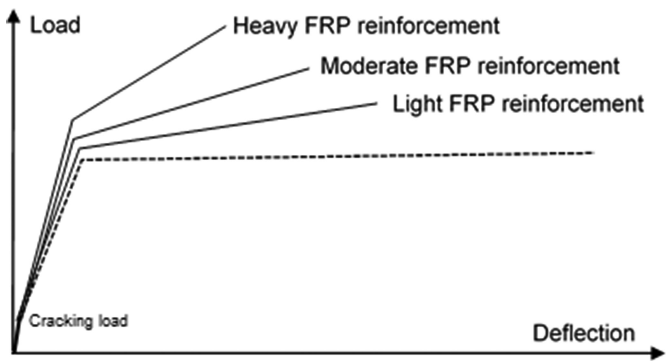


**Fig. 2.** Load-deflection curves for different degrees of flexural strengthening

## 2.4 Durability Considerations

In this chapter attention is given to the design considerations associated with durability. The chapter discusses durability of the FRP itself as well as of the whole strengthened system. The FRP-concrete interface is the critical component to the effectiveness of most FRP structural strengthening applications as this is the location where the transfer of stresses occurs.

## 2.5 Bond

Given the importance of the FRP-concrete bond interface, a dedicated chapter on bond has been introduced in this new bulletin (which was not the case in Bulletin 14), allowing the designer to have thorough understanding of behaviour aspects regarding bond interaction and providing background on bond failure mode verifications conducted as part of the design. Bond-slip laws are introduced both for surface bonded and near surface mounted FRP and a great deal of attention is given on various interfaces for bond failure which may occur. Debonding mechanisms are further classified on the basis of the location where debonding starts: *end debonding,* which occurs at the curtailment region of the FRP reinforcement, if it is not sufficiently anchored; and *intermediate crack debonding,* which occurs at an intermediate section along the beam by bridging cracks. Safety verifications with respect to these debonding mechanisms are provided, and further applied in the other chapters.

## 2.6 Ultimate Limit States for Predominantly Static Loading and Fatigue

This chapter basically follows Eurocode 2 format in discussing the ULS for the cases of bending with or without axial force (dealing with flexural strengthening as well as confinement), shear, torsion, punching, strut and tie models, anchorages and laps, and last but not least fatigue considerations. The analysis for the ultimate limit state may follow well-established procedures for reinforced concrete structures, provided that: the contribution of external FRP reinforcement is taken into account properly; and special consideration is given to the issue of bond between the concrete and the external reinforcement. The initial strain distribution during strengthening should be taken into account.

Typical load-deflection curves for an unstrengthened and three reinforced concrete beams strengthened in flexure are compared in Fig. 2. A considerable increase in the flexural load bearing capacity is obtained through the additional FRP reinforcement, at the expense of a reduction of the ultimate deflection at which the strengthened beam fails. The failure mode often tends to be of brittle nature, and may typically correspond to debonding between the FRP and the concrete, which forms a rather complex aspect of the calculation. Hereby, a number of design verification methods are provided, referring to different levels of approximation.

## 2.7 Serviceability Limit States

Reinforced (or prestressed) concrete elements with externally applied FRP should perform adequately in normal use. This SLS consideration is covered in Sect. 2.7 in terms of stresses, deflections, cracking and long term effects. As explained in the section on Basis of Design, the SLS might often govern.

Applied to the situation of Fig. 2, an increase in the stiffness of the cracked beam can be noted, depending on the amount of axial stiffness added to the beam through the FRP. The increased stiffness allows to limit deflections at service load level. In terms of cracking, typically more yet smaller cracks will be observed for the strengthened beam. The verification of stresses and deflections can be based on standard approaches. Compared to unstrengthened members the calculation becomes somewhat more complicated as the initial strain distribution during strengthening should be considered. To predict the crack width of elements strengthened in flexure, the influence of both the internal and external applied reinforcement, which have different bond behaviour, should be taken into account and for which an explicit calculation model is provided. Providing proper restriction of crack widths, no bond interface cracking is to be expected in the SLS.

## 2.8 Ultimate Limit States in Seismic Retrofitting

Seismic retrofitting of reinforced concrete structures with FRP may be used in order to upgrade a variety of structural deficiencies, if upon assessment according with the Eurocode 8 framework it is shown that seismic safety is insufficient. In Sect. 2.8, strategies in FRP interventions for seismic applications are provided, stressing the importance of considering clear objectives of the retrofit design and whereby the displacement demand and the pattern of its distribution may be essential prerequisites to the application of externally applied FRP for seismic retrofitting. Provisions are given on the seismic design of FRP as a means of enhancing strength and deformation capacity, strengthening of joints, preventing lap-splice failure, enhancing shear resistance, increasing rotation capacity and displacement ductility.

## 2.9 Detailing

Detailing rules give practical information on the location, arrangement and limitations for the FRP reinforcement required by considerations such as minimum ductility, functional requirements, adequate anchorage, applicability of calculation models, practical durability measures, environmental conditions, etc. Compared to other aspects of the FRP strengthening technique, requirements for detailing are much less supported by available test results. Nevertheless, detailing rules are important and if not attended may lead to premature failure of the strengthened structure.

## 2.10 Practical Execution and Quality Control

In the final chapter of the bulletin provisions and requirements are given concerning the practical execution of surface bonded and near surface mounted FRP. These deal with preceding repair and concrete soundness, application conditions and procedures, limitation of unevenness, etc. The application of EAR should be performed by qualified and trained workers (preferably, the EAR system and the applicators are certified by an independent certification body). This chapter also deals with the quality control aspects and gives detailed provisions (including test methods) with respect to characterization and quality control of the strengthening materials, qualification of workers, quality control on the practical execution, bond quality control after the practical execution and in-service inspection and maintenance.

## 3 Conclusion

An *fib* bulletin, called "Design of Concrete Members Strengthened with Externally Applied Reinforcement", is under publication for 2017. It gives detailed design guidelines on the use of EAR, the practical execution and the quality control, based on the vast amount of knowledge and innovations built over the years in this field and the expertise and state-of-the-art knowledge of the task group members. The bulletin gives comprehensive information, complementary to the coverage of FRP reinforcement in *fib* Model Code 2010 and running activities to introduce FRP reinforcement and strengthening of concrete structures with FRP in the next version of Eurocode 2. Special consideration has been given to various forms of EAR, including surface bonded reinforcement (often designated as externally bonded reinforcement), near surface mounted reinforcement and textile reinforced mortar. Mainly those aspects are covered which form the majority of the design problems for persistent load situations. Moreover, seismic retrofitting is covered extensively.

Further innovations in advanced materials for strengthening and rehabilitation applications continue to emerge. As a result, the bulletin is published as a progress report. To make the design of concrete members strengthened with EAR hands-on, fibT5.1 is currently working on a bulletin with design examples, which will also cover the use of FRP reinforcement for new structures.

**Acknowledgments.** The authors wish to acknowledge the *fib* Task Group 5.1 members for their support and their continuous involvement in the activities, as well as the supporting networks ENDURE (FP7) and COST TU1207.

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